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DEVELOPMENT OF THE TRANSIMS ENVIRONMENTAL MODULE

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Abstract

TRANSIMS is a simulation system for the analysis of transportation options in metropolitan areas. It's major functional components are: (1) a population disaggregation module, (2) a travel planning module, (3) a regional microsimulation module, and (4) an environmental module. In addition to the major functional components, it includes a strong underpining of simulation science and an analyst's tool box. The purpose of the environmental module is to translate traveler behavior into consequent air quality. The environmental module uses information from the TRANSIMS planner and the microsimulation and it supports the analyst's toolbox.

Transportation systems play a significant role in urban air quality, energy consumption and carbon-dioxide emissions. Recently, it has been found that current systems for estimating emissions of pollutants from transportation devices lead to significant inaccuracies. Most of the existing emission modules use very aggregate representations of traveler behavior and attempt to estimate emissions on typical driving cycles. However, recent data suggests that typical driving cycles produce relatively low emissions with most emissions coming from off-cycle driving, cold-starts, malfunctioning vehicles, and evaporative emissions. Furthermore, some portions of the off-cycle driving such as climbing steep grades are apt to be correlated with major meteorological features such as downslope winds. These linkages are important, but they are not systematically treated in the current modeling systems. This paper describes the development of a new modeling system to address these concerns.

Overview

Transportation activities contribute to excessive ozone, carbon-monoxide, and respirable particulate matter concentrations in urban areas. The air quality community has developed a number of tools to address these problems. Emissions typically have been estimated by assuming that people use driving patterns similar to those over which the emissions of vehicles have been tested. With these formulations, estimates of vehicle miles traveled and average speeds can be used to estimate emissions. This basic formulation has been supplemented by corrections for cold starts, evaporation from fuel tanks, and super-emitting vehicles. Recently, it has been found that current systems for estimating emissions of pollutants from transportation devices lead to significant inaccuracies (Oliver et al, 1993). One possible contributor to the inaccuracies results from deviations from the standard driving cycles that produce dramatically increased emissions (Kelly and Groblicki, 1993). Of particular concern is the effect of slopes because slopes also influence the local meteorology. When these inaccuracies are coupled to air quality models and limited meteorological data, it is difficult to tell whether the most appropriate path is being taken to achieve air quality goals (National Research Council, 1991).

The TRansportation ANalysis and SIMulation System (TRANSIMS) is being developed to address this problem as well as many other transportation analysis challenges. TRANSIMS is one part of the multi-track Travel Model Improvement Program sponsored by the U. S. Department of Transportation, the Environmental Protection Agency, and Department of Energy. Los Alamos National Laboratory is leading this major effort to develop new, integrated transportation and air quality forecasting procedures necessary to satisfy the Intermodal Surface Transportation Efficiency Act and the Clean Air Act and its amendments.

TRANSIMS is a set of integrated analytical and simulation models and supporting data bases. The TRANSIMS methods deal with individual behavioral units and proceed through several steps to estimate travel. TRANSIMS predicts trips for individual households, residents and vehicles rather than for zonal aggregations of households. TRANSIMS also predicts the movement of individual freight loads. A regional microsimulation executes the generated trips on the transportation network, modeling the individual vehicle interactions and predicting the transportation system performance.

The purpose of the TRANSIMS environmental module is to translate traveler behavior into consequent air quality, energy consumption, and carbon dioxide emissions. There are four major tasks required to translate traveler behavior into environmental consequences: (1) estimate the emissions, (2) describe the atmospheric conditions into which the contaminants are emitted, (3) describe the local transport and dispersion, and (4) describe the chemical reactions that occur during transport and dispersion of the contaminants.

The choice of components in the TRANSIMS approach is driven by the goal of representing those details that may influence the answer of the question being asked. In the context of travel the focus is on the individual traveler. In a same vein, the atmospheric model is chosen to be one that uses a relatively complete description of the physics of atmospheric circulation and includes an explicit treatment of the role of turbulence. The dispersion model is chosen to be a Monte-Carlo kernel model that can treat the effects of wind-shear, terrain flows and terrain-induced turbulence. The photochemical model is an airshed model.

Methodology

The TRANSIMS architecture includes four major elements: (1) a household and commercial activity disaggregation module, (2) an intermodal route planner, (3) a travel microsimulation module, and (4) an environmental module. The disaggregation module uses census and survey data to construct a regional synthetic population. In the future, it will also estimate travel related activities for each member of the synthetic population. Currently, travel activities are inferred from origin and destination matrices developed by regional planning authorities. The intermodal planner produces planned travel link by link and mode by mode on the travel network. The microsimulation module executes the planned travel over the urban area. The TRANSIMS environmental module is composed of a system of environmental modules that can describe both the average conditions and the fluctuations about the averages. It uses a prognostic meteorological model, HOTMAC, to describe the atmospheric conditions. The environmental module will use modal emissions models to define the emissions. Transport and dispersion of conservative pollutants will be described with a Monte-Carlo Kernel model (RAPTAD). Air chemistry will be described by an airshed model with the current choice being the CIT model developed at the California Institute of Technology and the Carnegie Mellon Institute of Technology

Input for the system will consist of surface characteristics, large-scale meteorology, terrain, traveler behavior, and vehicle characteristics. Terrain and surface characteristics for current conditions are available for US cities. For future applications, estimates will have to be made of the changes expected from the current conditions. The required large-scale meteorology is available through airport radio balloon soundings or through meteorological analyses done by the National Meteorological Center.

Household and Commercial Activity Disaggregation Module

The disaggregation module includes two components: (1) a synthetic population submodule and (2) an activity demand submodule. The synthetic population is developed from the Census Standard Tape File 3 (STF-3) and the Public Use Microdata Sample (PUMS). The PUMS has all the desired attributes of the population but it represents a sample from a much larger population than desired while the STF-3 represents a much smaller population, but it doesn't provide all the information of interest. A statistical technique called iterative proportional fitting is used to estimate the desired data at the census tract or block group level based on the PUMS correlations. The actual synthetic population is randomly drawn from the multi-way tables produced by iterative proportional fitting.

The activity demand module is not yet developed. In the interim, a module that uses the metropolitan planning organization's estimated origin and destination tables to produce synthetic activities is being used.

The Intermodal Route Planner

The planner generates routes for each load from the activity-based travel demand. A load is a traveler or a commodity. A trip plan is a sequence of modes, routes and planned departure and arrival times at the origin, destination(s), and mode changing facilities to move the load to its activity locations. We assume that travel demand derives from a load's desire or need to perform activities. The household and commercial activity disaggregration module provides the planner with disaggregated activity demand and travel behavior. The planner assigns activities, modes, and routes to individual loads in the form of trip plans. The individual trip plans are input to the travel microsimulation for its analysis.

Trip plan selection is related directly to a load's desire to satisfy individual (or in the case of freight, corporate) goals. Goals measure a trip plan's acceptability and depend on the load's socioeconomic attributes and trip purpose. Typical goals include cost, time, and distance minimization, and safety and security maximization. The load's objective is to minimize the deviations from these goals.

The travel demand problem is formulated as a mathematical program based on a multi-goal objective function. The Planner's solution method has four phases: (1) trip generation, (2) goal measurement, (3) preference adjustment, and (4) trip plan superposition. In the first three phases, the individual's travel behavior preferences such as departure time or origin-destination directness, are adjusted iteratively to satisfy the travel goals. After every load has a feasible trip plan, the fourth phase superimposes all trip plans on one another in space and time. The network characteristics are then updated based upon the projected interaction of all trips and steps (1) through (4) are repeated.

Travel Microsimulation

The Travel Microsimulation module mimics the movement and interactions of travelers throughout a metropolitan region's transportation system. The approach is to use a cellular automata (CA) microsimulation. CA traffic models divide the transportation network into a finite number of cells. In the current form each cell's length is the average distance between vehicles when traffic is at a complete standstill. A cell may be empty or contain a single vehicle. If it contains a vehicle, the vehicle has an integer velocity between zero and maximum velocity, Vmax=5. The integer velocity represents the number of cells that vehicle moves the next step. The step size is exactly one second, in which case Vmax corresponds to 135 km/hour, or about 84 mph. This step size abets fast computation because the updated vehicle position is computed by integer arithmetic and without multiplication of velocity and time step.

Updating the vehicle's next velocity and position is quite simple. First, we define the number of unoccupied cells ahead of the vehicle as its "gap". Then, we update the velocity by accelerating to the maximum velocity without running into the vehicle ahead:

$$V(t+1)=\min[V(t)+1,\mathrm{Vmax},\mathrm{gap}].$$

But, with probability P, we reduce this tentative velocity by one (without going backwards):

$$V(t+1)=\max[V(t+1)-1,0].$$

Finally, we update the vehicle's position:

$$X(t+1)=X(t)+V(t+1).$$

This rule set is called the Nagel-Schreckenberg model. The random velocity reduction process captures driver behavior such as free-speed driving fluctuations, non-deterministic accelerations, and overreactions when braking. The simple one-lane model has been extended to cover lane changing, passing, merging, and turning behaviors.

The simple model produces dynamics observable in everyday freeway traffic. First, we can display an individual vehicle's movement in space and time as shown in Figure 1. Vehicles moving at constant velocity leave straight-line tracks slanting downward to the right. A stopped vehicle moves in time, but not in space, creating a vertical line. The figure shows the spontaneous formation of well-known traffic shock waves that propagate backward in space.

This model also produces the fundamental flow-density relationship shown in Figure 2 where density has been normalized to 1.0 for a completely jammed system. At low densities, flow increases linearly with more vehicles in the system. Near a density of 0.1 the system achieves maximum throughput or 'capacity,' but the flow is quite chaotic and its variability increases dramatically.

Emissions Modules

An essential component for TRANSIMS is an emissions model that can give emissions specific to the type of driving being done. There is one such model in existence now that uses a so-called engine map to define the emissions. The model called VEHSIME (Carlson et al 1994) was developed from a fuel economy model called VEHSIM. One disadvantage of this model is that it needs measurements of the emissions of each vehicle type as a function of engine load. In fact, there are relatively few cars for which such measurements are available. Consequently, VEHSIME is viewed as an intermediate solution, which will permit us to gain experience with TRANSIMS. In the longer term, an approach based on the physics and chemistry of the automobile engine will be used. Investigators at the University of Michigan (An, 1993) are working on such a model.

We also expect to use the results of work being done at Georgia Tech, the California Air Resources Board, National Cooperative HIghway Research Program, and EPA.

Our work with VEHSIME discovered a number of deficiencies. The original VEHSIME engine maps produced fuel economies and emissions that were somewhat different than were reported for similar vehicles in the EPA fuel economy and emission databases. We chose to adjust the engine maps in such a way as to provide results from VEHSIME that were more representative of the values reported by the EPA. The results of these adjustments produced modified engine maps that approximately matched the EPA fuel economy measurements for similar vehicles and matched the EPA tailpipe emissions for NOX, CO, and hydrocarbons for the highway driving cycle.

An illustration of the use of the modal emissions model is shown in Figure 3. Figure 3 describes the average CO emissions while driving half the time up the specified grade and half the time down the grade with a distribution of speeds and accelerations derived from EPA's three cities study (USEPA,1993). The Camaro is a 350 cubic-inch-displacement model and it is not affected by any but the highest grades, while the effects are much greater for lower powered cars.

There are three other elements to the motor vehicle emissions module: (1) evaporative emissions, (2) cold start emissions, and (3) malfunctioning-vehicle emissions. Evaporative emissions are captured in a canister that is purged during vehicle operation. If the vehicle is not operated for a long time the canister becomes full and the fuel is evaporated and released to the atmosphere. We have the evaporative emissions model used in Mobile 5A and we are incorporating it into our emissions module. The TRANSIMS planner will provide information on the vehicles that are in use or idle so that we will be able to tell when the canister is full and the emissions are released to the atmosphere.

A vehicle starting with a cold engine has considerably higher emissions than one with an engine at normal operating temperature. There are two reasons for this. When the engine is cold, the commanded air-fuel mixture is rich in fuel compared to the ideal stoichiometric conditions normally commanded for an engine and thus there is not enough oxygen in the air-fuel mixture to completely combust the fuel. This increased fuel is commanded to reduce the tendency of the engine to stall when it is cold and to compensate for poor mixing and fuel conditions in the intake manifold. The incomplete combustion of the fuel results in emissions of CO and hydrocarbons that cannot be completely handled by the catalytic converter. Also the catalytic converter will not start working until it reaches the "light-off" temperature. Thus if there is a situation where many of the vehicles in the fleet are taking frequent short trips, the cold-start emissions can account for a significant fraction of the vehicle's emissions. We are currently using a formulation wherein the CO engine-out emissions are multiplied by five during startup (Ross at al, 1996) and the catalyst transitions from zero effectiveness to the level obtained from a hot catalyst. This formulation will be refined in the future.

The last large source of emissions that has not been modeled precisely is emissions from malfunctioning vehicles. Measurements have indicated that emissions from as little as 10% of the vehicles can account for most of the emissions. Some of the uncertainty in the measurements of high emitting vehicles is because vehicles with properly functioning emissions control systems can have very high emissions if they are under high engine load at the time of the measurement. Thus there is some doubt whether the vehicles identified in measurements as high emitters have continuous high emissions or were measured during the short time they had high emissions caused by engine load. Initially, we are going to divide the vehicles into two sets: (1) those with damaged catalysts (probably about 10% of the fleet, based on remote sensing data) and (2) those with malfunctioning fuel metering systems (probably about 0.1% of the fleet). Remote sensing data will be used to estimate the fraction of the fleet in each category and the average catalyst efficiency for those with impaired catalysts. We will estimate the emissions from damaged fuel metering systems by using VEHSIME with high accelerations and high grades to force enrichment behavior.

In the longer term, University of Michigan investigators plan to develop models describing vehicles with engine problems and with malfunctioning emissions control systems. Once these models have been developed, we plan to incorporate them into TRANSIMS.

The primary output of the transportation micro-simulation module will be summarized cellular-automata (CA) data. The CA describes the vehicle position in units of cells, velocity in units of cells per second and the acceleration in units of cells per second per second. A typical cell size is 7.5 meters so that the resulting motion, in 16 mph increments, is too coarse to be used directly as input to the emissions module. We are developing an approach to produce realistic, smooth vehicle trajectories that can be used in the emissions module. The current prototype estimates the probability of an acceleration or deceleration from the fraction of the speeds that change in a spatial cell and speed bin. Once the fraction of vehicles that are accelerating is known, the fraction with a specific acceleration is calculated by using conditional probabilities derived from EPA's three cities study (USEPA, 1993). Currently the acceleration and deceleration probabilities are used with a Kalman filter to produce smooth trajectories.

We have done some testing of the use of the filter. We began with actual vehicle trajectories from a database developed by the California Air Resource Board (Effa and Larson, 1993). We overlaid a grid on the vehicle's trajectory and deduced equivalent CA positions and velocities. The trajectories were grouped into 10 sets; three sets of arterials, slow, medium, and fast, and 7 freeway sets ordered by increasing congestion. The most uncongested freeway set had average speeds of about 60 mph while the most congested set had average speeds of about 10 mph. In each case we used only the first 30 seconds of the driving. From the synthetic CA data we collected the fraction of the vehicles in each CA speed bin in each CA cell plus the fraction that increased CA speeds in a cell and the fraction that decreased speeds in a cell. The resulting data was used as input to the filter.

The averages of speeds, CO emissions, NOX emissions, hydrocarbon emissions, and fuel consumption were compared to those from the original trajectories. Figure 4 reports such a comparison for CO emissions for a medium speed freeway link. Figure 5 reports such a comparison for NOx emissions for a medium speed freeway segment, while Figure 6 gives the comparison for hydrocarbon emissions on a medium speed freeway link. The average speeds on the medium speed freeway link are shown in Figure 7. Figures 8 through 11 show the comparisons for a very congested freeway link for CO, NOx, hydrocarbon emissions and average speeds respectively. Overall the comparisons show the need for further development, but they also show that the system can produce respectable results over a wide range of driving conditions.

Meteorological Module

The meteorological module is HOTMAC (Higher Order Turbulence Model for Atmospheric Circulation). HOTMAC is a three-dimensional time-dependent model (Williams et al, 1995). It uses the hydrostatic approximation and a terrain-following coordinate system. HOTMAC solves conservation relations for the horizontal wind components, potential temperature, moisture, turbulent kinetic energy, and the turbulence length scale. HOTMAC describes advection (properties moving with the wind), Coriolis effects (motion induced by the earth's rotation), and turbulent transfer of heat, momentum, and moisture. It also describes solar and terrestrial radiation effects of forest and urban canopies. The lower boundary conditions are defined by a surface energy balance and similarity theory. The soil heat flux is obtained by solving a heat conduction equation that ignores lateral heat flux. In an urban context, the surface energy balance requires an additional term that represents the heat released by human activities. The additional heat, along with differences in thermal and albedo properties between urban and non-urban surfaces, produces the urban heat island.

HOTMAC uses two major sets of inputs: (1) topography and (2) a single vertical profile of winds, temperatures, and relative humidity. The topography consists of terrain heights at half grid intervals over the domain and indices that show the land use or land coverage of each computational cell. For existing situations, the land use/land coverage is available in commercial databases or can be deduced from satellite images. The meteorological profile is used to describe the synoptic (large-scale) conditions of winds, temperatures, and moisture. The model is initialized with the potential temperature assumed to be the same in every location for any given height above mean sea level. Potential temperature is the temperature of a parcel of air adiabatically compressed to sea-level pressure. In a well-mixed atmosphere, the potential temperature tends to be constant with height except for very near the surface. On the lateral boundaries the winds, moisture, and temperatures are the result of solving a one-dimensional form of the model in which parameters vary only in the vertical direction. The placement of the boundaries is normally chosen so that all the major terrain influences on the region of interest are included within the computational grid.

Mesoscale models, such as HOTMAC, are designed for circumstances in which the local terrain influences are significant and make the meteorology more predictable than might otherwise be the case. HOTMAC has been used successfully in many contexts. It has been used in the Geysers region of California that is in the Pacific Coast Range near the Pacific Ocean. It has been used to describe flow in narrow, deep canyons of western Colorado. It has described the formation and dissipation of clouds during evening hours over the south coast of England. It has successfully described the linked sea-breeze between the Pacific Ocean and the Japanese Alps. It has also been used on sub-continental transport problems in the eastern US and the southwestern US. It was used in the Mexico City Air Quality Research Initiative, and it is currently being used by officials in Mexico City to plan their air quality improvement program.

HOTMAC provides grid-averaged winds, temperatures, moisture, clouds, and turbulent wind energies for the model domains that cover hundreds of kilometers with a maximum resolution of about one kilometer. HOTMAC does not describe the complex motion found in urban street canyons. As a result of vehicle emissions in urban areas, air pollution can become trapped between buildings in what is called an "urban canyon". Studies have shown that air pollution concentrations can be 2 to 10 times higher in an urban canyon than in the case without buildings. Typically, a large recirculation zone forms between the buildings that transports the traffic emissions from street-level to building top. However, only a small portion of the air pollution is vented out of the urban street canyon top, as the buildings cause the air flow within the canyon to become separated from the larger-scale air flow above.

Our approach for accounting for the urban canyon effect on air pollution concentrations will consist of two levels of sophistication: first, a derivation of a simple parameterization that can be easily implemented into our existing modeling system to roughly approximate the urban canyon effect and second, development of a microscale air flow model for explicitly simulating the air flow in the urban canyon.

In the first approach, an urban-canyon-induced eddy circulation will be added to the dispersion model RAPTAD to approximate the entrapment of air pollution between buildings. In the second approach, we will develop a finite difference Navier-Stokes numerical flow model jointly with researchers from the Theoretical Division of Los Alamos National Laboratory. The computer model will allow for explicit simulation of many different building configurations and flow scenarios. In addition, the computer model can be used to improve the parameterization used in the RAPTAD model.

Local Transport and Dispersion Module

The dispersion module will be based on the RAPTAD (Random Particle Transport and Dispersion) model (Yamada and Bunker, 1988). Pseudo-particles are transported with instantaneous velocities that include the mean wind field and the turbulence velocities. The turbulence velocity is generated randomly so that it is consistent with the standard deviation of the wind at the particle location. The location of each pseudo-particle represents the center of mass of a concentration distribution for the volume of air that encloses the material associated with the pseudo-particle (puff). The total concentration at any point is obtained by adding the concentration contributions of each puff at that point (a kernel method). The Monte Carlo kernel method requires that a functional form for the distribution kernel be chosen and that parameters that describe the width, breadth, and depth of the distribution be calculated. Our approach assumes a Gaussian distribution where particle position variances are determined from the time integration of the velocity variances encountered over the history of the puff. The position variances are estimated based on the random force theory of turbulent diffusion (Lee and Stone, 1982). The random force theory is also known as the Brownian-motion analogy, or the Langevin model in which an equation describes the motion of particles under the influence of random accelerations and a resistive force term. Lee and Stone extend the theory to the treatment of clusters of particles from finite-size, finite-duration sources.

The system has many advantages for applications involving complex terrain. The use of a higher-order turbulence model means that there are three-dimensional, time-dependent, wind fields and turbulence fields available for the representation of dispersion and transport. Transport can be treated in more detail because important terrain influences are represented in both the mean fields and the turbulence fields. An example of the importance of a more sophisticated treatment of dispersion is afforded by the following real-world example. A tracer material was released for one hour in a valley in Utah and some 65 monitors were used to record the concentrations. During the night few monitors actually recorded significant amounts of tracer because the plume was so narrow during nighttime conditions. The measurements showed that the concentrations measured at ten km downwind extended for several hours. Gaussian puff calculations gave low concentrations for all hours except one. RAPTAD gave concentrations that remained high for a few hours. The Gaussian puff model moved all the material with the same wind speed. In actuality, some of the material near the ground moved very slowly, while some aloft moved much more rapidly. RAPTAD treated the wind speed differences and provided a much better description of the actual pollution behavior.

Air Chemistry Module

The air chemistry module will be the CIT airshed model (Russell, et al, 1988), or, possibly, the Urban Airshed Model. Both models have been used with HOTMAC output, and there are other components of the environmental module that must be developed before an airshed model is applied. In either case the area to be modeled is divided into an Eulerian three-dimensional grid. The equations that describe the pollutant concentration are solved within each cell of the grid, which imposes a large computational effort. The concentration of species may vary by the incorporation of new emissions, transport of chemical species in and out of each cell, dilution, and chemical reactions, all as a function of time. One advantage of this type of model is geographical resolution for control strategies and impacts. Both models are continually being improved; for example, a major focus of the current work on the CIT model is to extend the formulation to address organic aerosols. The extension to organic aerosols and the improvements to the treatment of inorganic aerosol formation is very important because of the increased concern over fine particles in the urban setting.

Summary of Major Features

The TRANSIMS environmental module will include: (1) a modal emissions module, (2) a prognostic meteorological module, (3) a Monte-Carlo kernel dispersion module, and (4) an airshed air chemistry module. It will require inputs from the TRANSIMS planner and traffic microsimulation. It will estimate emissions of relevant species and it will use large-scale meteorology and land coverage to estimate concentrations of ozone, secondary aerosols, carbon-monoxide, nitrogen-dioxide, sulfur dioxide, and respirable particulate matter.

It will be capable of estimating both mean concentrations and fluctuations about the mean concentrations. It will also be able to estimate nitrate deposition. It will be a flexible tool for "what if" questions and it can be applied to any city given appropriate topography and surface characteristics. It will be a good platform for future improvements.

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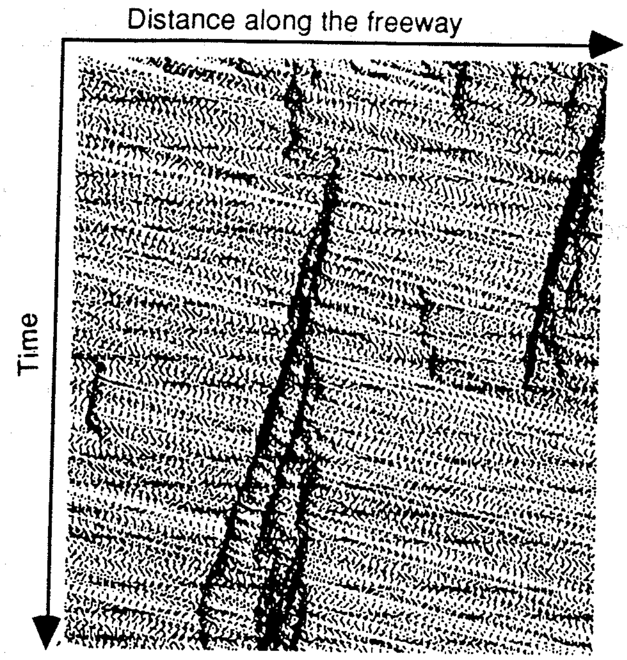

Figure 1. Waterfall plot of traffic dynamics produced by a cellular automata model.

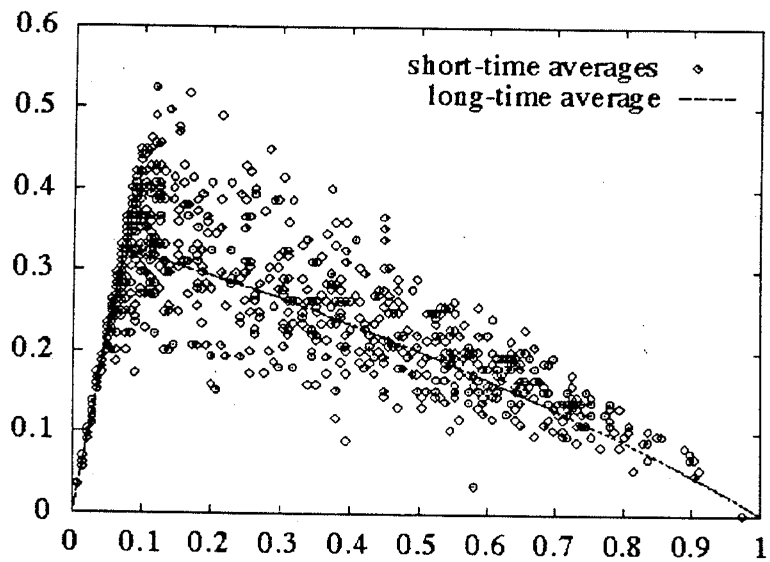

Figure 2. Fundamental flow-density relationships produced by a cellular automata model.

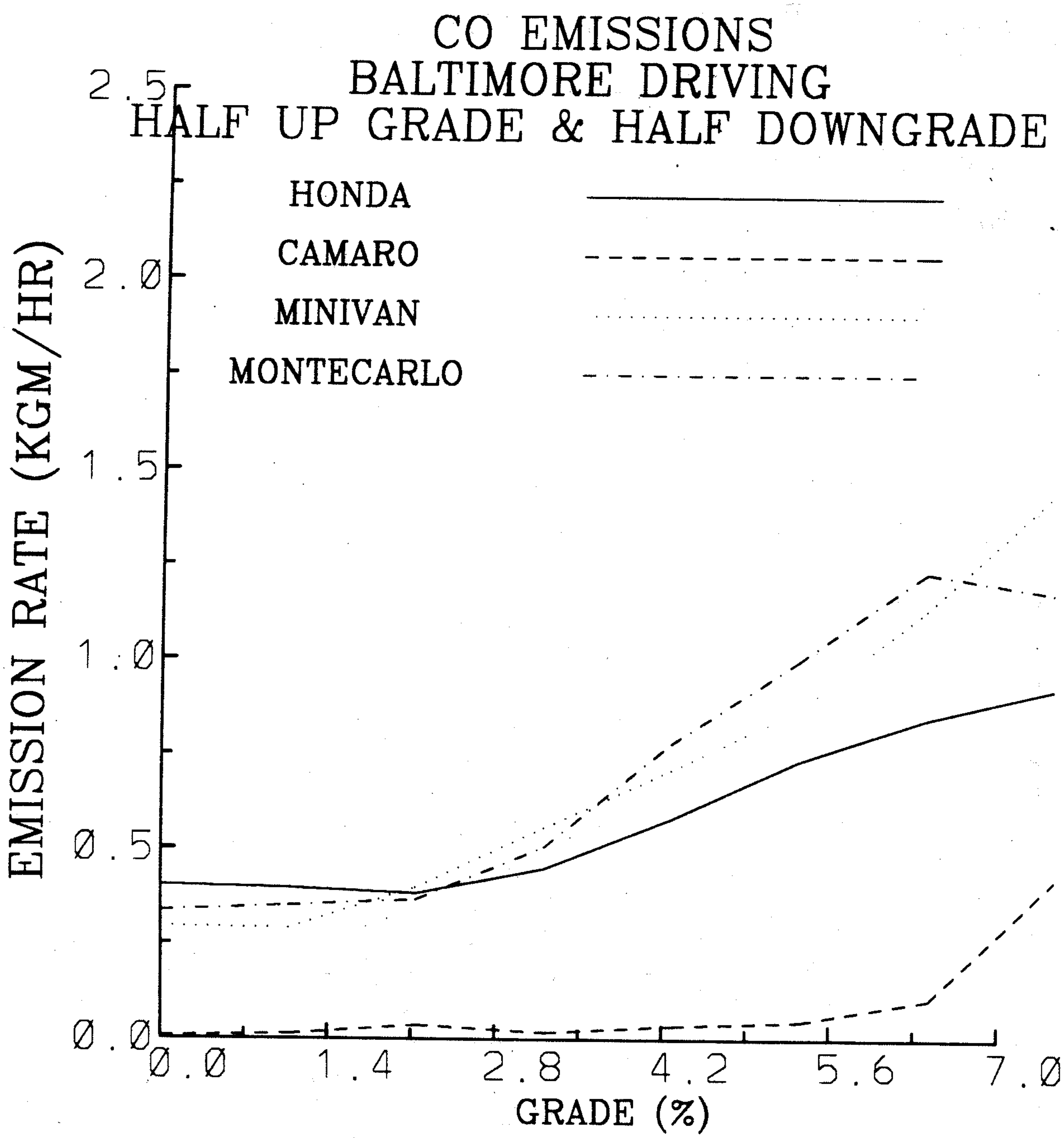

Figure 3. Average CO emissions from VEHSIME for vehicles driving with speed and acceleration distributions derived from the EPA three cities study with half the driving up the specified grade and half down the grade.

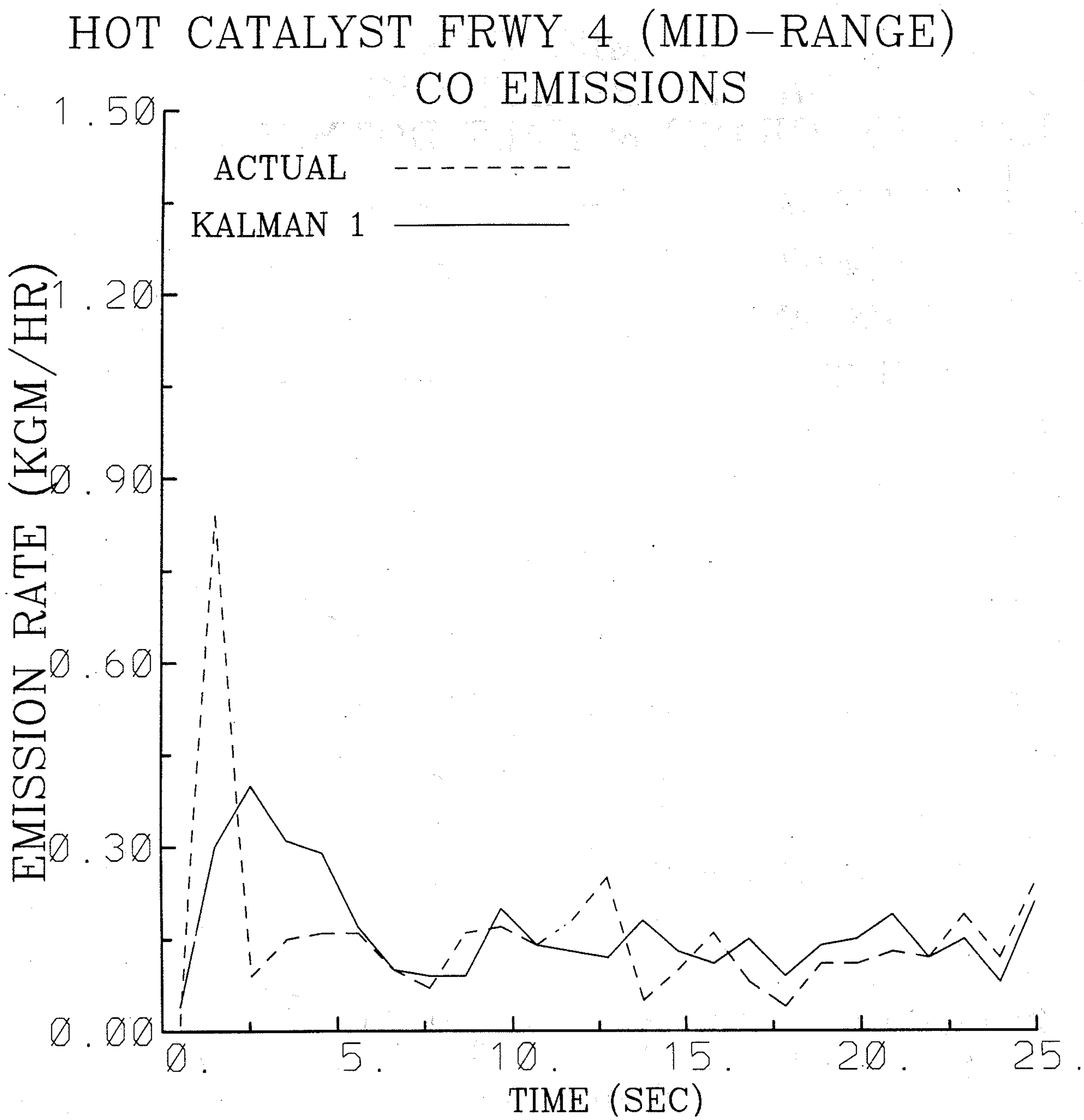

Figure 4. Comparison between average CO emissions estimated from VEHSIME with real driving on a moderately congested freeway link and those produced from synthetic CA data on the same link.

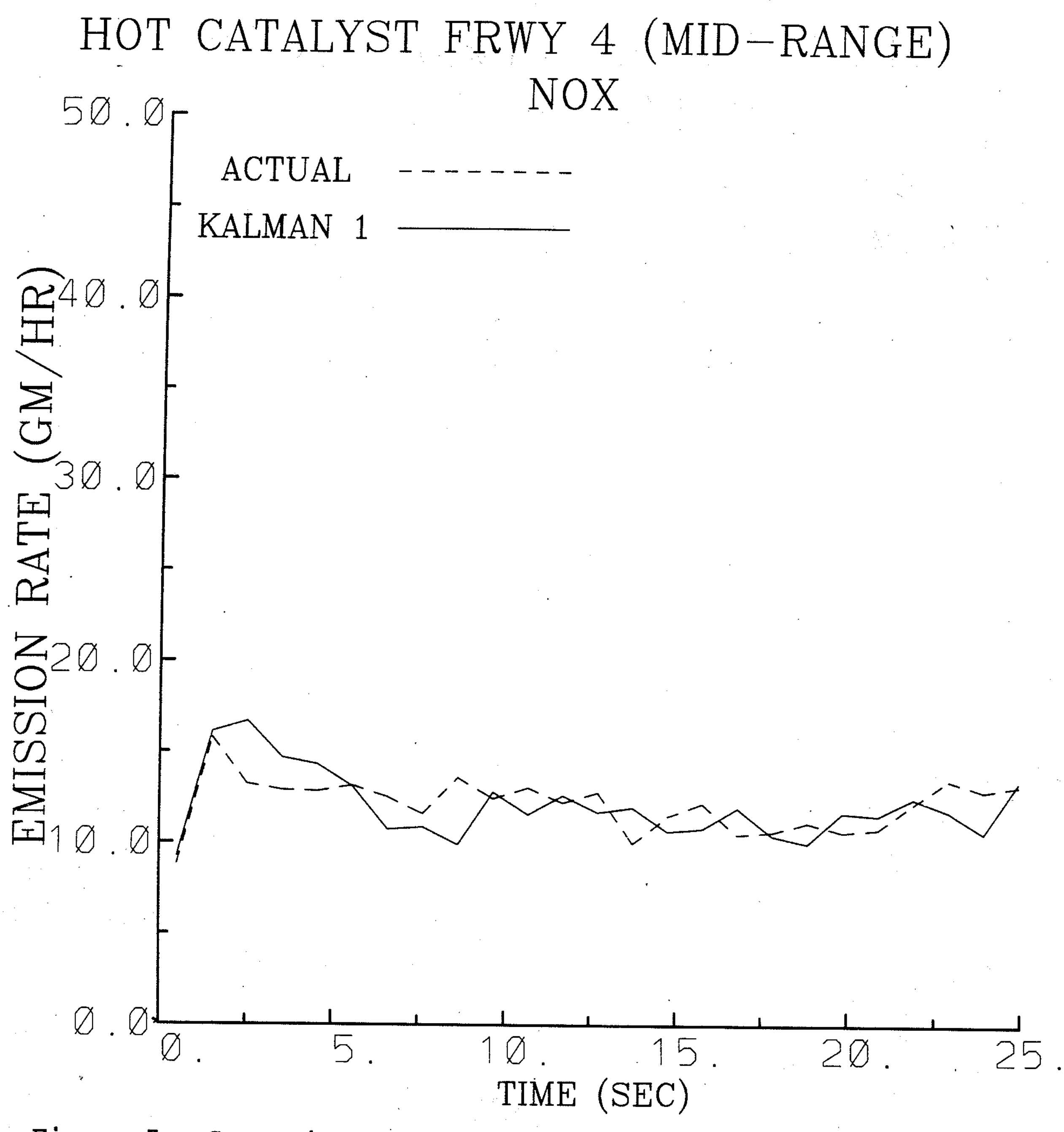

Figure 5. Comparison between average NOx emissions estimated from VEHSIME with real driving on a moderately congested freeway link and those produced from synthetic CA data on the same link.

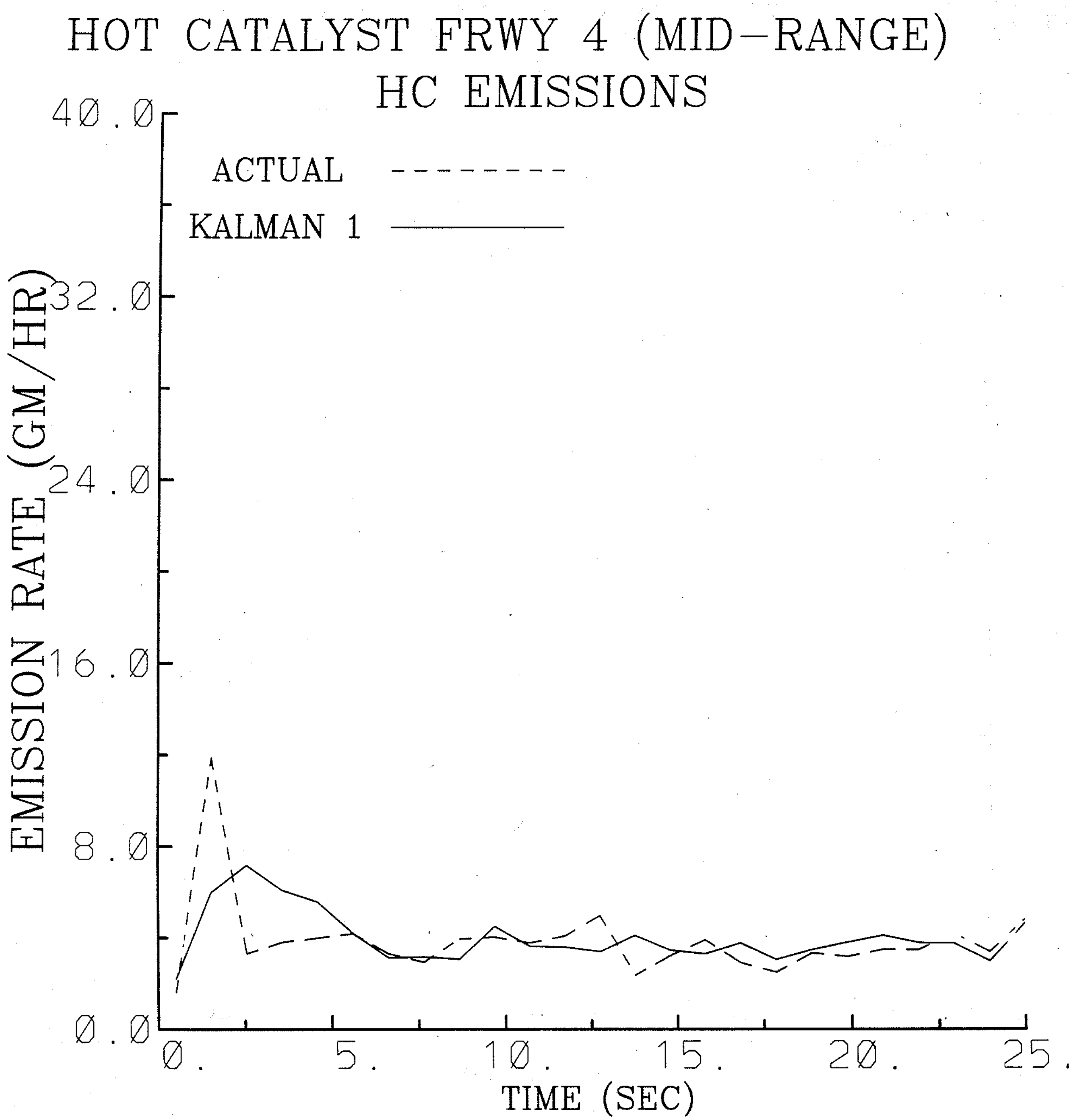

Figure 6. Comparison between average hydrocarbon emissions estimated from VEHSIME with real driving on a moderately congested freeway link and those produced from synthetic CA data on the same link.

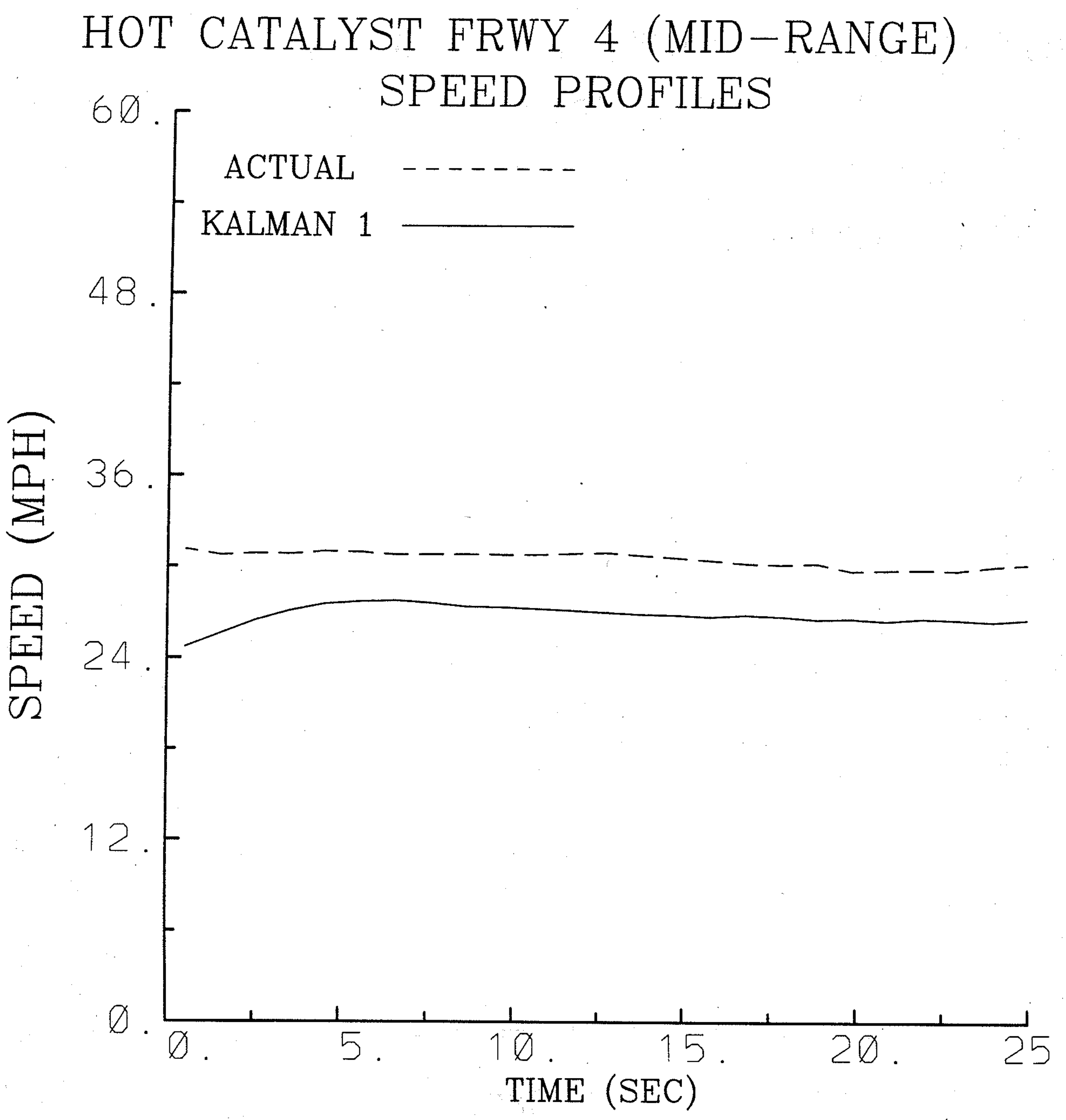

Figure 7. Comparison between average speeds with real driving on a moderately congested freeway link and those produced from synthetic CA data on the same link.

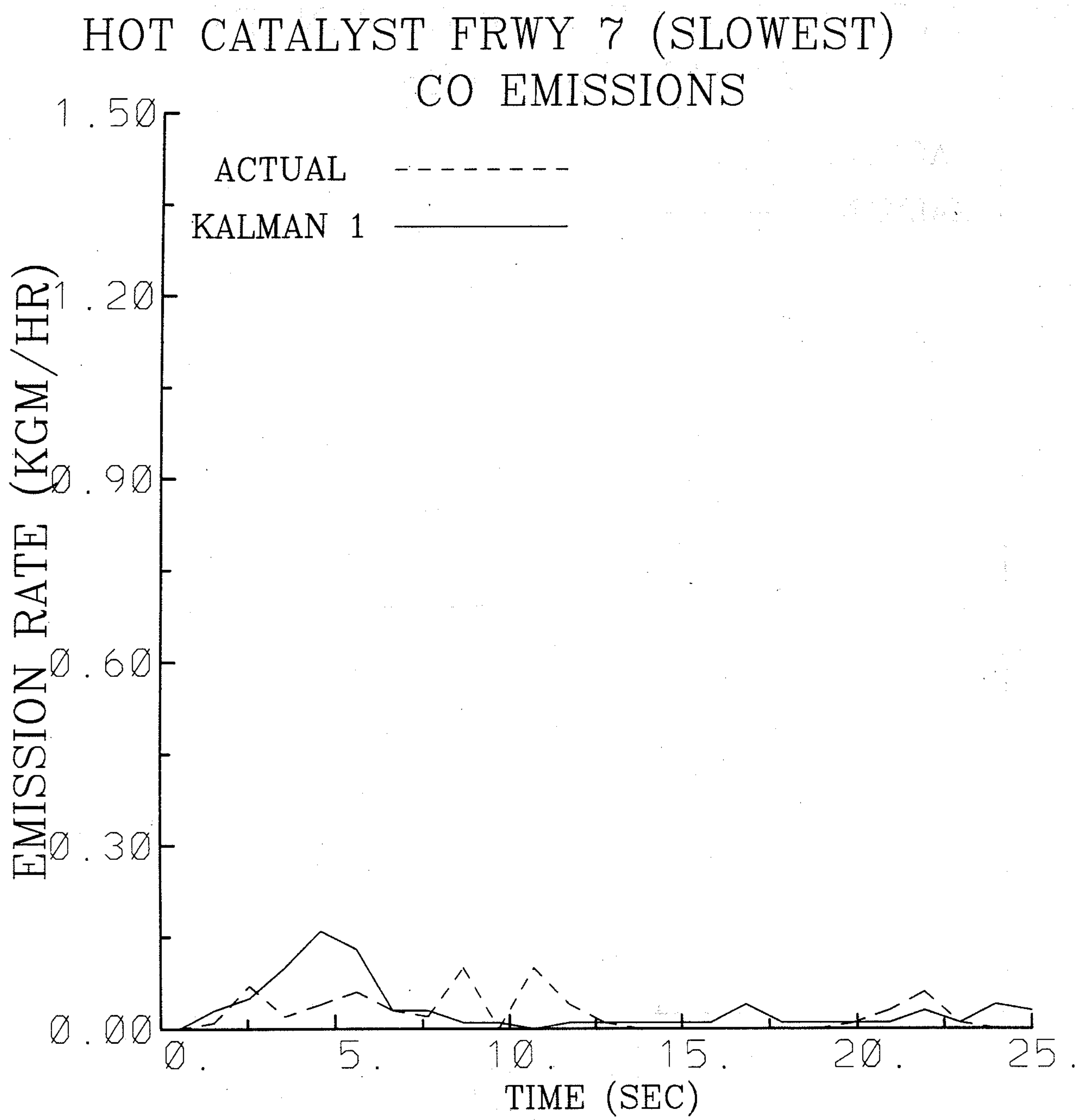

Figure 8. Comparison between average CO emissions estimated from VEHSIME with real driving on a very congested freeway link and those produced from synthetic CA data on the same link.

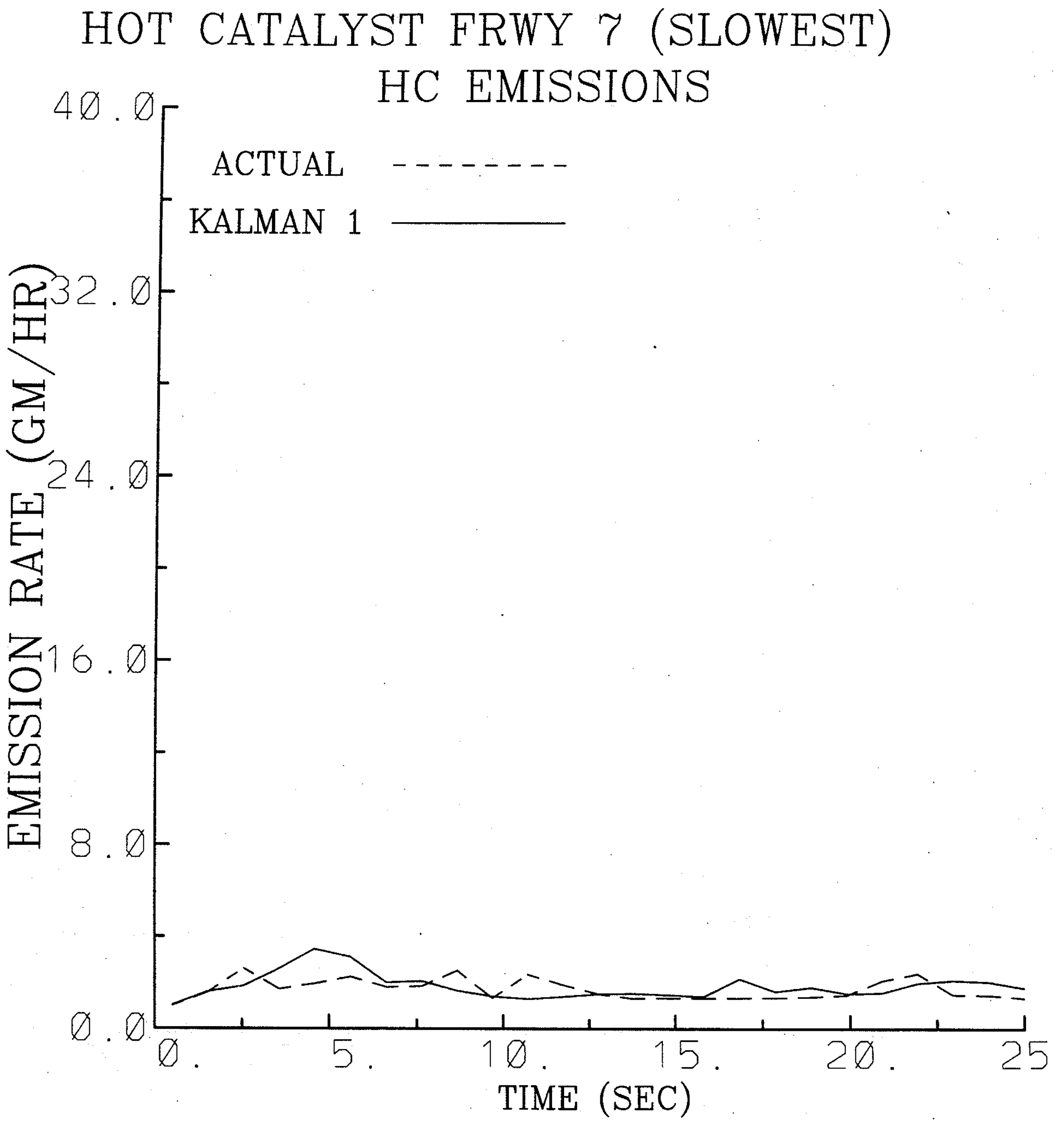

Figure 9. Comparison between average NOx emissions estimated from VEHSIME with real driving on a very congested freeway link and those produced from synthetic CA data on the same link.

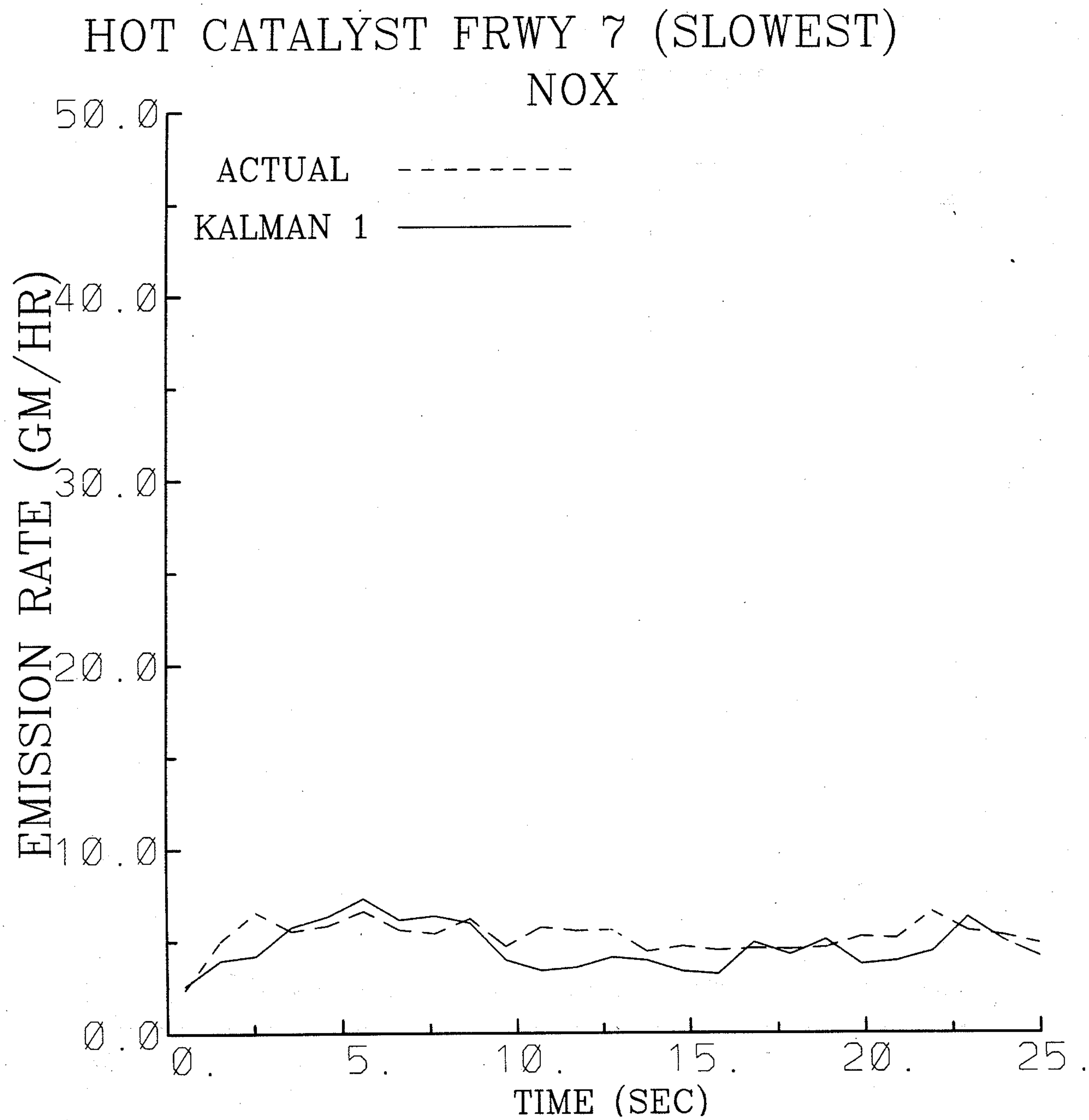

Figure 10. Comparison between average hydrocarbon emissions estimated from VEHSIME with real driving on a very congested freeway link and those produced from synthetic CA data on the same link.

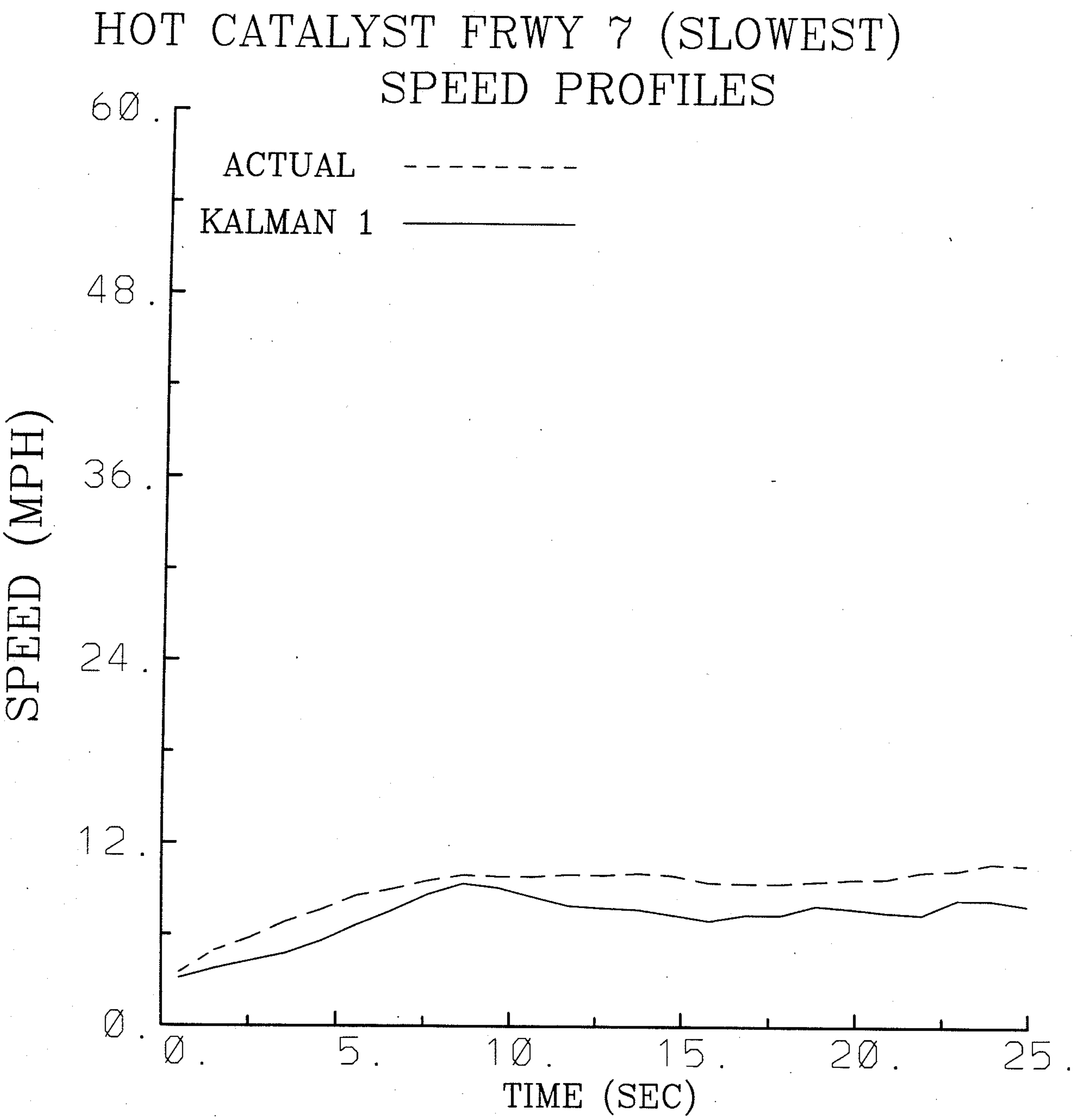

Figure 11. Comparison between average speeds with real driving on a very congested freeway link and those produced from synthetic CA data on the same link.